1.0 INTRODUCTION

1.1 Purpose & Location

The Rosedale Waste Water Treatment Plant Outfall Tunnel project was undertaken as part of a larger Waste Water Treatment Plant expansion. The project was designed in response to the growing population of the region and the need to expand the municipal infrastructure. The chosen solution was a combined tunnel and seabed outfall under Mairangi Bay, on the North Shore of Auckland, New Zealand, which would discharge effluent of tertiary quality 2.6 km offshore. The existing outfall fails to meet the discharge distance standards and the new outfall is due to be operational by the end of 2010.

1.2 Tunneled Section

The tunnel was designed to be approximately 3km long and segmentally lined. To minimize settlement on the surface the tunnel boring machine (TBM) chosen to excavate the tunnel was the LOVAT RME131SE Series 24400, capable of mining the expected ground conditions in open or closed mode, due to the potential settlement through the onshore section of the new outfall. At the time this paper was written, approximately 2,800 m of the tunneled section had been completed and the remainder was expected to finish shortly.

2.0 PROJECT

2.1 Geology & Ground Water Conditions

The surface geology along the tunnel alignment comprises of residual soils, completely weathered volcanic ash and recent and Pleistocene deposits. Below these materials the ground consists of East Coast Bay Formation (ECBF), a Miocene marine sedimentary sequence consisting of moderately weathered to un-weathered sandstones, siltstones and mudstones with probable cemented packets and lenses or poorly sorted sand to boulder-sized conglomerate (Parnell Grit). The tunnel is expected to be entirely within the ECBF, which according to the
Geotechnical Baseline Report (GBR) has an intact rock strength of 3 – 30 MPa. For the entire tunnel alignment one fault of up to 2 m intersected length of highly disturbed ground, comprising of rock fragments with soft clay gouge, is anticipated.

Complex groundwater conditions were expected along the tunnel alignment, with a wide range of water pressures being present within the ECBF and overlying soils. No single groundwater table was identified and there were early indications that the ECBF and the overlying perched groundwater systems were in fact interconnected. Further pump testing confirmed that the groundwater systems were interconnected. The GBR specified water pressure of up to 4 bar and inflow rates 0.3 – 5 litres/second.

2.2 Alignment

The onshore section of the tunnel was driven from a permanent drop shaft in the vicinity of the existing Rosedale Waste Water Treatment Plant, heading approximately 2,400 m North-East, lying entirely underneath public and North Shore City Council owned land. The offshore section of the tunnel started from an access shaft near the shore of Mairangi Bay and continued North-East for approximately 600 m, ending under the seabed at a transition/riser shaft. The tunnel had a minimum radius of curvature of 200 m and was driven at a downhill grade of approximately 1.1%.

3.0 TBM DESIGN

3.1 General

The TBM was designed to operate under moderately high earth and hydrostatic pressure, with all systems designed to function under approximately 7 bar. The TBM was designed to be capable of negotiating a 150 m radius horizontal and vertical curve.

3.2 Cuttinghead

For the Rosedale Waste Water Treatment Plant Outfall Tunnel project a mixed-face, three spoke type cuttinghead with face isolation doors was deemed to be the most appropriate design, as seen in Figure 3.

The cuttinghead was equipped with soft ground cutting tools; consisting of 25 no. ripper teeth, 18 no. scraper teeth and a centre nose cutter. The ripper teeth and the centre nose cutter incorporated Tungsten Carbide inserts to improve excavation efficiency and aid in abrasion resistance. The scraper teeth were only installed at the outer end of the spokes, to leave as much open space as possible towards the centre. This was done to discourage muck from accumulating and clogging the centre section of the cuttinghead.
Two of the ripper teeth that were installed on the gauge of the cuttinghead were equipped with an internal pressurized oil circuit, to monitor cutting tool wear. The wear monitoring system provided the TBM operator with notice, via the Programmable Logic Controller (PLC), when the tools were nearing the end of their designed usage. The wear monitoring system provided an early stage of protection against excessive wear on the cutting tools and cuttinghead face.

The ripper teeth were mounted in Adaptor Boxes, allowing the TBM to be equipped with 305 mm diameter Disc Cutters should harder rock be encountered during tunneling.

3.3 Main Drive

The TBM utilized a hydraulic type main drive consisting of 6 no. drive units, powered by 2 no. 262 kW electric motors. The Main Drive was designed to produce the following Torque and Speed values (accounting for system inefficiency, \( \alpha = 4.9 \)):

- Maximum Torque: \( 1,413 \text{ kN\cdot m} \) @ 2.7 rpm
- Minimum Torque: \( 618 \text{ kN\cdot m} \) @ 6.1 rpm
- Peak Torque: \( 1,766 \text{ kN\cdot m} \)

The main drive sealing system was designed to withstand pressures up to 7 bar, as expected along the alignment. A combination of oil pressurized seals and a grease purge system kept muck from contaminating the bearing.

3.4 Propulsion

The propulsion system of the TBM consisted of 12 no. hydraulic cylinders, producing a maximum thrust of 13,530 kN and having a standard operating thrust of 9,415 kN. The orientation of the cylinders was designed not to push on any segment joints, in any ring position.

3.5 Articulation Systems

In order to negotiate the curves in the alignment, the TBM was equipped with both passive and active articulation systems.

The active articulation system consisted of 8 no. hydraulic cylinders, producing a maximum thrust of 9,025 kN and having a standard operating thrust of 6,275 kN. The active articulation system enabled steering of up to 2.6° in any direction.

The passive articulation system consisted of 8 no. hydraulic cylinders, producing a maximum tension of approximately 4,600 kN. The passive articulation system was used to hold the trailing shield at appropriate angles to move through the curves in the alignment.
3.6 Ground Condition System

The TBM was equipped with a ground conditioning system (GCS) to achieve a muck consistency that would enable efficient excavation. The system had a foam injection capacity of up to 1,200 litres/min, measured at an expansion ratio of 10:1 at atmospheric pressure. There were 3 no. GCS injection ports on the cuttinghead face, 3 no. in the cuttinghead chamber and 3 no. along the casing of the screw conveyor. The ground conditioning system is an integral component of any earth pressure balance (EPB) type TBM. For this project, the GCS was of particular importance as the ECBF material that was being mined required careful conditioning to prevent the extremely sticky muck from clogging the TBM components. Proper ground conditioning also serves to reduce the torque required by the cuttinghead to excavate the ground and provides for easier transfer of muck through the screw conveyor. Due to local regulations, biodegradable and environmentally safe conditioning agents were used throughout.

3.7 Dewatering System

The TBM was equipped with a dewatering system capable of pumping up to 5 litre/sec at the maximum head expected from the invert area of the TBM. Piping along the trailing gantry collected water from the segment unloader area and carried it to a 2 no. chamber settling tank mounted on the trailing gantry. The tank was used for sludge separation before discharge of the water along the tunnel.

4.0 PROJECT CHALLENGES

4.1 Surface Settlement

The project geotechnical reports stated that surface settlement was highly probable due to the interconnectivity of the local groundwater systems. Tunneling in the ECBF material was likely to result in depressurization of the groundwater in the residual soils above, resulting in surface settlement which was expected to be in the range of 60 – 200 mm. [2]

However, during the course of the project initial surface settlement measurements showed there was little to no effect as a result of the draining of any water present in the ECBF.

4.2 Ground Conditions

4.2.1 Water Inflows

Throughout the drive severe ground water inflows were experienced at the tunnel face. In total, 6 no. major events occurred, ranging from 2 – 160 m in longitudinal extent. The Geotechnical Baseline Report for the project specified the expected groundwater inflows to be on the order of 0.3 litre/sec at the tunnel face, except for at the fault zones where 5 litre/sec could be expected. During tunneling operations, actual water inflows of >60 litres/sec were experienced, appearing to have an infinite supply (ie. no drop in pressure, despite constant draining through the TBM). The water pressures ranged from 0.5 – 6 bar, as recorded on the EPB sensors.

Figure 4: Ground water inflow through segments
4.2.2 Expected Geology

The ECBF is a weak rock formation with strengths typically on the order of 5 MPa, however Parnell Grit in limited quantities was likely to occur within the ECBF matrix and strengths could potentially be on the order of 60 MPa.

As was found on a previously completed tunneling project in the region, mechanical excavation of the ECBF material causes it become very sticky. In its natural state the water content of the ECBF is close to the plastic limit of the pulverized fraction. Thus, the mechanical excavation process at the application of water becomes a trigger for clay stickiness. Destructuring occurs because silt-sized particles, some of which are aggregations of clay particles, are relatively weakly bonded. Under the influence of severe mechanical working the clay aggregations may be disaggregated and release clay mineral particles. The resulting plasticity and swelling behavior depends on the mineralogy of the released clay, which for ECBF is Smectite. This has implications for the operation of a closed mode TBM using a screw conveyor, as the cuttinghead openings, working chamber and auger flights can rapidly become clogged with swelling clay. [3,4]

4.2.3 Unexpected Geology

On a number of occasions the material encountered was described as gravels to cobbles in a matrix of un-cemented sand and silt, this being interpreted as Albany Conglomerate which was not anticipated as being within the tunnel alignment. This material was found on the full excavation face, indicating a layer greater than 3.3 m thick. Fragments of this material as seen from the outlet of the screw conveyor are seen in Figure 5.

There were also a number of events where the ECBF was highly fractured, resulting in high grout takes. Mining in both this fractured ground and the Albany Conglomerate resulted in large water flows. The flows, in conjunction with the high pressures and ground not suitable for EPB tunneling meant a loss of the water-tightness of the TBM and extremely slow production rates, along with safety concerns for the TBM and most importantly the personnel operating it.

4.3 Alignment & Surveying

The tight alignment gave cause for concern, in terms of both segment damage and the ability to drive the tunnel to the required tolerance, which were on the order of ± 100 mm. As there were no intermediate shafts until after tunnel construction, there was also a concern with regards to making the connections at the Mairangi Beach shaft and the transition between the tunnel sections and the marine works.

The downhill grade and access shaft depth posed several problems. The tunnel logistics were a concern, particularly locomotive sizing and space constraints for services. These constraints also affected the size and capacity of the dewatering pump, creating a risk for inundation of the TBM.
4.4 Segment Interaction

The initial design of the TBM segment unloader and back-up gantries specified that they rode on skids, directly on the tunnel segments. This led to considerable damage to the invert segment radial joints, as seen in Figure 6.

5.0 SOLUTIONS

5.1 Surface Settlement

To date, surface settlement on this project has been of no issue, even when the ECBF groundwater system was allowed to flow freely. Free-flowing water occurred regularly and as a precaution against the differing ground conditions and to minimize any potential settlement, the TBM was run in closed mode for the majority of the tunnel construction.

5.2 Ground Conditions

While the TBM was equipped with safe guards against water inflows in the form of a guillotine closure system on the screw conveyor and a dedicated dewatering system, there were still issues with excess water in the TBM. One reason for the ingress of water was a blockage of the screw conveyor guillotine closure system due to a build-up of material, which subsequently damaged the system. Also, large quantities of rock in the differing ground prevented a plug from being formed in the screw conveyor. The resulting water inflows were combated by a number of mitigation measures including: a change in methodology to allow for clean-up, a secondary guillotine door, upgraded ground conditioning systems (emergency power from secondary generator, boost tanks & pumps within tunnel) and operating in closed mode at all times when mining in expected conditions.

The damage to the guillotine door was repaired and a second closure system was added to further safe guard against the ground water ingress. The secondary door was a flap-type closure mounted at the screw conveyor discharge. A valve was added to the door to enable the controlled release of water.
To effectively mine in the ECBF material careful conditioning of the muck was necessary. It was found on previous projects that basic foam was an effective conditioning agent to prevent clogging and was utilized on the Rosedale project. Control of the water content of the muck was important and depended heavily on the amount of water found in the rock. The resulting spoil was the consistency of a “porridge” like substance [3]. Through the use of foams and polymer the stickiness of the ECBF was overcome, although it was evident that the foam mixture had a great affect on the advance rates achieved. A 5% change in the mixture was found to change the advance rate from 150 mm/min to 5 mm/min in a short time frame with eventual blockage occurring.

5.3 Alignment & Surveying

The alignment was followed with only minor deviations and Weizbach Triangles were completed on a weekly basis to track and confirm the progress. After 2.4 km a survey hole was drilled to find the Mairangi Beach Shaft. This hole found the mark and a survey from the tunnel to a line in the shaft showed that the total error over this distance was 1 mm on bearing and 44 mm on chainage, giving confidence that the TBM and transition riser would meet within the required tolerances.

5.4 Segment Interaction

Numerous modifications were made to the unloader tubs, including the addition of bogie wheels to the leading edge. The modifications improved the condition of the invert segments, however remedial work was still required on the caulking grove.

Figure 8: Unloader bogie wheels
6.0 RESULTS

The TBM achieved the following productions rates during tunneling operations completed to date:

Average Production per Day: 23 no. Rings

Best Production Day: 34 no. Rings

Best Production Week: 162 no. Rings

(Note: Ring Width of 1m)

Due to the unexpected differing ground conditions, daily productions rates varied from 3 – 10 m. Figure 9 illustrates the production rates achieved.

7.0 CONCLUSION

The primary challenge of a TBM manufacturer and contractor is to design and build a machine to suit the expected geology of the project. Access to geotechnical data from the outset of a project is of great importance to all parties involved. Adapting to unexpected challenges during mining is another challenge facing both parties. By incorporating specialized components into the design and utilizing feedback obtained during mining, the TBM manufacturer and contractor were able to produce a TBM that successfully mined in challenging conditions for the construction of the Rosedale Waste Water Treatment Plant Outfall Tunnel.

8.0 REFERENCES

[1] LOVAT Archives


[4] Atkinson, Fookes, Miglio, Pettifer; Destructuring and Disaggregation of Mercia Mudstone during Full-Face Tunnelling; Q J Eng Geology Hydrogeology (36); 2003; pp. 296-303